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Description

Technical field

- 5 The present invention relates to the field of renewable energy, and more specifically relates to the measurement of the resource for wind turbines, namely the wind, for the purposes of controlling (orientation, torque and speed regulation) and/or diagnosing and/or monitoring the wind turbine.
- 10 A wind turbine allows the kinetic energy of the wind to be converted into electrical or mechanical energy. In order to convert wind into electrical energy, it is made up of the following elements:
- 15
- a mast allowing a rotor to be placed at a sufficient height to allow it to move (required for horizontal axis wind turbines) or allowing this rotor to be placed at a height that allows it to be driven by a stronger and steadier wind than at ground
 - 20 level. The mast generally houses some of the electrical and electronic components (modulator, control unit, multiplier, generator, etc.);
 - a nacelle mounted at the top of the mast housing mechanical
 - 25 and pneumatic components and some electrical and electronic components that are required for operating the machine. The nacelle can turn in order to orient the machine in the correct direction;
 - a rotor, fixed to the nacelle, comprising a plurality of blades
 - 30 (in general three) and the nose cone of the wind turbine. The rotor is driven by the energy of the wind, it is directly or indirectly connected by a mechanical shaft (via a gearbox and mechanical shaft system) to an electric machine (electric
 - 35 generator, etc.) that converts the harvested energy into electrical energy. The rotor is potentially provided with control systems, such as variable pitch blades or aerodynamic brakes;

- a transmission, made up of two axes (mechanical shaft of the rotor and mechanical shaft of the electric machine) connected by a transmission (gearbox).

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Since the beginning of the 1990s, there has been renewed interest in wind turbine energy, particularly in the European Union where the rate of annual growth is approximately 20%. This growth is attributed to the inherent possibility of producing electricity without carbon emissions. In order to support this growth, the output of wind turbines must continue to be improved. The perspective of increasing wind turbine energy production requires the development of efficient production tools and of advanced control tools for improving the performance capabilities of the machines. Wind turbines are designed to produce electricity at the lowest possible cost. Consequently, wind turbines are generally constructed in order to achieve their maximum performance for a wind speed of approximately 15 m/s. Wind turbines do not need to be designed that maximize their output at higher wind speeds, since these are infrequent. In the case of wind speeds above 15 m/s, some of the additional energy contained in the wind needs to be lost in order to avoid any damage to the wind turbine. Therefore, all wind turbines are designed with a power regulation system.

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With respect to this regulation of the power, controllers are designed for variable speed aerogenerators. The aims of the controllers are to maximize the recovered electrical power, to minimize the speed fluctuations of the rotor and to minimize the fatigue and the extreme moments of the structure (blades, mast and platform).

30

Prior art

35 In order to optimize control, it is important that the wind speed at the rotor of the wind turbine is known. To this end, various techniques have been developed.

According to a first technique, the use of an anemometer allows a wind speed to be estimated at a point, but this imprecise technology does not allow the whole of a wind field to be measured or does not allow the three-dimensional components of the wind speed to be known.

According to a second technique, a LIDAR ("Light Detection and Ranging") sensor can be used. LIDAR is remote sensing or optical measurement technology based on analyzing the properties of a beam sent towards its transmitter. This method is particularly used to determine the distance to an object by means of a pulse laser. Unlike radar based on a similar principle, the LIDAR sensor uses visible or infrared light instead of radio waves. The distance to an object or to a surface is provided by measuring the delay between the pulse and the detection of the reflected signal.

In the field of wind turbines, the LIDAR sensor is heralded as being a sensor that is essential for the correct operation of large wind turbines, especially when their size and their power increases (currently, 5 MW, soon 12 MW for offshore applications). This sensor allows remote measuring of the wind, initially allowing the wind turbines to be calibrated so that they can provide maximum power (optimization of the power curve). For this calibration step, the sensor can be positioned on the ground and oriented vertically (profile), which allows the wind speed and its direction to be measured, as well as the wind gradient according to the altitudes. This application is especially critical since it allows the energy-producing resource to be known. This is important for wind turbine projects, since this affects the financial viability of the project.

A second application involves placing this sensor on the nacelle of the wind turbine to measure the wind field in front of the wind turbine by being oriented practically horizontally. A priori, measuring the wind field in front of the wind turbine provides advance knowledge of the turbulence that the wind

turbine will encounter a few instants later. However, the current techniques for controlling and for monitoring a wind turbine do not allow a measurement to be taken into account that is carried out by a LIDAR sensor by precisely estimating the wind speed at the rotor, i.e. in the rotor plane. Such an application is particularly described in patent application FR 3013777 (US 2015/145253).

Furthermore, over the last decade, there has been increasing interest in the behaviour of the wind formed upstream of a wind turbine, i.e. the induction zone. Within the induction zone, the wind is slowed down due to the presence and the operation of the wind speed, which collects some of the aerodynamic power of the wind. A better understanding of the induction zone allows the control strategies that are based on a LIDAR sensor, as well as the evaluations of the power of the wind turbines, to be improved. In the first case, the aim is to use upstream wind measurements to predict the wind speed on the rotor plane. In this latter case, the purpose is to establish the connection between the power and the speed of the free current, namely the wind speed that would have occurred at a point corresponding to the position of the turbine (wind turbine) in the absence of the wind turbine. For this work, the benefit of the induction zone resides in the use of measurements in the vicinity of the turbine for estimating the effective wind speed of the rotor.

In the document by "Emmanuel Simon Pierre Branlard and Alexander Raul Meyer Forsting, 'Using a cylindrical vortex model to assess the induction zone in front of aligned and yawed rotors', in: EWEA Offshore 2015 Conference, European Wind Energy Association (EWEA), 2015", analytical formulae for the speed field induced by a cylindrical vortex wake model are applied to assess the induction zone. The results are compared to actuator disk simulations for different operating conditions.

In the document by "D. Medici, Stefan Ivanell, J-A Dahlberg, and P. Henrik Alfredsson, 'The upstream flow of a wind turbine: blockage effect', in: Wind Energy 14.5 (2011), pg 691-697", the

wind tunnel measurements are used to study the induction zone of different wind turbines. Furthermore, the results were compared with an analytical expression of the induction zone obtained from a linear vortex cylinder model.

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In the document "Eric Simley, Nikolas Angelou, Torben Mikkelsen, Mikael Sjöholm, Jakob Mann, and Lucy Y Pao, 'Characterization of wind velocities in the upstream induction zone of a wind turbine using scanning continuous-wave lidars', in: Journal of Renewable and Sustainable Energy 8.1 (2016), pg 013301", the induction zone of a wind turbine is studied using a LIDAR sensor with synchronized continuous waves. It has been shown that the standard deviation of the longitudinal speed component remains relatively unchanged when the wind approaches the rotor, whereas the standard deviation of the vertical and lateral component increase slightly.

In the document "Niels Troldborg and Alexander Raul Meyer Forsting, 'A simple model of the wind turbine induction zone derived from numerical simulations', in: Wind Energy 20.12 (2017), pg 2011-2020", the induction zone in front of different wind turbines is studied by combining Navier Stokes simulations in the stationary state and an actuator disk approach. It has been shown that, for distances beyond one times the radius of the rotor upstream of the rotor, the induced velocity is similar and independent of the geometry of the rotor.

For all the approaches from literature, it is worthwhile highlighting that the induction zone is computed/estimated off-line using simulations or experimental data. Furthermore, the induction zone is presumed to be implicitly constant for a given wind speed, once identified. Apparently, this induction zone provides very average information with respect to the wind speed deficit, since it is clear that the induction zone is a function of the angles of blades and of yaw for a given wind speed. It is for this reason that these methods do not allow online and continuous determination of the physical phenomena implemented in the induction zone.

Summary of the invention

In order to overcome these disadvantages, the present invention
5 relates to a method for determining a wind induction factor for
a wind turbine equipped with a LIDAR sensor. For this method,
measurements of the wind speed are carried out in a plurality
of measurement planes by means of the LIDAR sensor, then
induction factors are determined between the measurement planes
10 by means of the measurements and of a linear Kalman filter, and
the induction factor between a measurement plane and the plane
of the rotor of the wind turbine are deduced therefrom by means
of a second linear Kalman filter. Thus, by virtue of the LIDAR
sensor and of the Kalman filters, the invention allows simple,
15 efficient and continuous updating of the induction zone.

The invention also relates to a method for determining the wind
speed in the rotor plane, a method for controlling a wind turbine,
and a method for diagnosing a wind turbine, with these methods
20 using the induction factor determined by the method according
to the invention. [1]
[SEP]

The present invention relates to a method for determining a wind
induction factor between a measurement plane and the rotor plane
25 of a wind turbine, said wind turbine being equipped with a LIDAR
sensor carrying out a measurement relating to the wind speed in
at least three measurement planes remote from said wind turbine,
said wind induction factor representing a wind braking
coefficient between two separate points upstream of said wind
30 turbine, with the braking resulting from the operation of the
wind turbine in the wind field. The following steps are
implemented for this method:

a) the wind speed is measured in at least three measurement
35 planes remote from said wind turbine by means of said LIDAR
sensor;

b) at least two wind induction factors are determined between

two of said measurement planes by means of said measurements of the wind speed at said measurement planes and of a linear Kalman filter; and

5 c) said wind induction factor is determined between a measurement plane and said rotor plane of said wind turbine by means of said induction factors between two determined measurement planes and by means of a linear Kalman filter.

10 According to one embodiment, said at least two wind induction factors are determined between said measurement planes with known spacings, preferably with the same spacing, and preferably the spacing is equal to the distance between said rotor plane and the measurement plane closest to said rotor plane.

15 According to one implementation, said measurement of the wind speed is carried out in at least four measurement planes, and at least three wind induction factors are determined between two measurement planes.

20 Furthermore, the invention relates to a method for determining the wind speed in the rotor plane of a wind turbine equipped with a LIDAR sensor. The following steps are implemented for this method:

25 a) a wind induction factor is determined between a measurement plane and the rotor plane of a wind turbine by means of the method according to any of the preceding features; and

30 b) said wind speed in the rotor plane is determined as a function of said wind induction factor between a measurement plane and the rotor plane of a wind turbine and by measuring the wind speed in the measurement plane relative to said wind induction factor.

35 According to one embodiment, the wind speed in the rotor plane corresponds to the multiplication of the wind induction factor between a measurement plane and the rotor plane of a wind turbine

by said wind speed in the measurement plane relative to said wind induction factor.

Moreover, the invention relates to a method for controlling a wind turbine equipped with a LIDAR sensor. The following steps are implemented for this method:

a) the wind speed is determined in the rotor plane of said wind turbine by means of the method according to any of the preceding features;

b) said wind turbine is controlled as a function of said wind speed at the rotor plane.

The invention also relates to a method for diagnosing and/or monitoring a wind turbine equipped with a LIDAR sensor. The following steps are implemented for this method:

a) a wind induction factor is determined between a measurement plane and the rotor plane of a wind turbine by means of the method according to any of the preceding features;

b) the aerodynamic power collected from the wind by said wind turbine is determined by means of said wind induction factor determined between a measurement plane and the rotor plane of a wind turbine; and

c) the operation of said wind turbine is diagnosed and/or monitored by means of said determined collected aerodynamic power.

According to one aspect, the invention relates to a computer program product comprising code instructions designed to implement the steps of a method according to any of the preceding features, when the program is executed on a processing unit of said LIDAR sensor.

Furthermore, the invention relates to a LIDAR sensor for a wind

turbine comprising a processing unit implementing a method according to any of the preceding features.

Moreover, the invention relates to a wind turbine comprising a LIDAR sensor according to any of the preceding features, said LIDAR sensor preferably being placed on the nacelle of said wind turbine.

Further features and advantages of the method according to the invention will become apparent from reading the following description of non-limiting embodiments, with reference to the accompanying figures that are described hereafter.

List of figures

Figure 1 illustrates a wind turbine equipped with a LIDAR sensor according to one embodiment of the invention.

Figure 2 illustrates the steps of the method for determining a wind induction factor according to one embodiment of the invention.

Figure 3 illustrates the steps of the method for determining the wind speed according to one embodiment of the invention.

Figure 4 illustrates the steps of the method for controlling a wind turbine according to one embodiment of the invention.

Figure 5 illustrates the steps of the method for diagnosing a wind turbine according to one embodiment of the invention.

Figure 6 illustrates the development over time of three induction factors between measurement planes obtained by means of the method according to one embodiment of the invention.

Figure 7 illustrates the development of the induction factor as a function of the distance relative to the rotor plane for a given time obtained by means of the method according to one

embodiment of the invention.

Figure 8 illustrates the development over time of the wind induction factor in the rotor plane obtained by means of the method according to one embodiment of the invention.

Figure 9 illustrates the development of the induction factor as a function of induction as a function of the distance relative to the rotor plane for a given time obtained by means of the method according to one embodiment of the invention.

Description of the embodiments

The invention relates to a method for measuring the resource of wind turbines: namely the wind, in particular for the purposes of controlling (orientation, torque and speed regulation) and/or diagnosing and/or monitoring the wind turbine, whereby the wind turbine is controlled and/or monitored as a function of the determination of a wind induction factor, with the wind turbine being equipped with a LIDAR sensor for carrying out this estimation.

The induction factor is a braking coefficient of the wind in the induction zone of the wind turbine. Indeed, the wind is slowed down in the upstream zone of the wind turbine by the presence of the wind turbine and its operation: in other words, the power collected by the wind turbine causes the wind to brake upstream of the wind turbine. Thus, the induction factor represents a physical phenomenon, and provides an indication relative to the resource of the wind turbine. The induction factor is computed between two planes upstream of the wind turbine, by definition, it corresponds to the speed ratio between these planes. By denoting the induction factor as a , the wind speed as u , and the respective distances of the two considered planes with respect to the rotor plane as d_1 and d_2 , the induction factor between the planes located at distances d_1 and d_2 from the rotor plane can be expressed as:

$$a_{d1,d2} = \frac{u_{d1}}{u_{d2}}.$$

When one of the considered planes is the rotor plane, then $d1 = 0$.

5

According to the invention, the LIDAR sensor allows the wind speed to be measured on a plurality (at least three) of measurement planes upstream of the wind turbine. There are several types of LIDAR sensors, for example, scanned LIDAR, 10 continuous LIDAR or pulsed LIDAR sensors. Within the scope of the invention, a pulsed LIDAR is preferably used. However, the other LIDAR technologies can be used whilst remaining within the scope of the invention.

15 The LIDAR sensor allows rapid measurement. Consequently, the use of such a sensor allows rapid continuous determination of the wind induction factor. For example, the sampling rate of the LIDAR sensor can range between 1 and 5 Hz, and can equal 4 Hz.

20 Figure 1 shows, schematically and non-limiting manner, a horizontal axis wind turbine 1 equipped with a LIDAR sensor 2 for the method according to one embodiment of the invention. The LIDAR sensor 2 is used to measure the wind speed at a given distance over a plurality of measurement planes PM (only two 25 measurement planes are shown). Advance knowledge of the wind measurement a priori allows considerable information to be provided. This figure also shows the x, y and z axes. The reference point of this coordinate system is the centre of the rotor. The x direction is the longitudinal direction, 30 corresponding to the direction of the axis of the rotor, upstream of the wind turbine, this direction also corresponds to the measurement direction of the LIDAR sensor 2. The y direction, perpendicular to the x direction, is the lateral direction located in a horizontal plane (the x, y directions form a horizontal plane). The z direction is the vertical direction 35 (substantially corresponding to the direction of the mast 4) directed upwards, the z axis is perpendicular to the x and y

axes. The rotor plane is shown by the dot-and-dash line rectangle PR, it is defined by the y, z directions for a zero x value. The measurement planes PM are planes formed by the y, z directions at a distance from the rotor plane PR (for a non-zero x value).

5 The measurement planes PM are parallel to the rotor plane PR.

Conventionally, a wind turbine 1 allows the kinetic energy of the wind to be converted into electrical or mechanical energy. In order to convert wind into electrical energy, it is made up
10 of the following elements:

- a mast 4 allowing a rotor (not shown) to be placed at a sufficient height to allow it to move (required for horizontal axis wind turbines) or allowing this rotor to be placed at a
15 height allowing it to be driven by a stronger and steadier wind than at ground level 6. The mast 4 generally houses some of the electrical and electronic components (modulator, control unit, multiplier, generator, etc.);

20 - a nacelle 3 mounted at the top of the mast 4, housing mechanical and pneumatic components, some electrical and electronic components (not shown), that are required for operating the machine. The nacelle 3 can turn to orient the machine in the correct direction;

25 - the rotor, fixed to the nacelle, comprising a plurality of blades 7 (generally three) and the nose cone of the wind turbine. The rotor is driven by the energy of the wind, it is directly or indirectly connected by a mechanical shaft (via a gearbox and
30 mechanical shaft system) to an electric machine (electric generator, etc.) (not shown), which converts the harvested energy into electrical energy. The rotor is potentially provided with control systems, such as variable pitch blades or aerodynamic brakes;

35 - a transmission, made up of two axes (mechanical shaft of the rotor and mechanical shaft of the electric machine) connected by a transmission (gearbox) (not shown).

As shown in figure 1, which is an embodiment of a pulsed LIDAR sensor, the LIDAR sensor 2 that is used comprises four measurement beams or axes (b1, b2, b3, b4). In a non-limiting manner, the method according to the invention also operates with a LIDAR sensor comprising any number of beams. The LIDAR sensor takes a one-off measurement at each point of intersection of a measurement plane PM and of a beam (b1, b2, b3, b4). These measurement points are shown by black circles in figure 1. Processing the measurements at these measurement points allows the wind speed to be determined in the measurement planes PM. To this end, the wind modelling method described in French patent application under file number FR 1755675 can be applied in particular.

Preferably, the LIDAR sensor 2 can be mounted on the nacelle 3 of the wind turbine 1.

According to the invention, the method for determining a wind induction factor between a measurement plane and the rotor plane of a wind turbine comprises the following steps:

1) measuring the wind speed;

2) determining induction factors between measurement planes;

3) determining the induction factor between a measurement plane and the rotor plane.

Figure 2 illustrates, schematically and in a non-limiting manner, the steps of the method according to the invention. The first step is a step of measuring (MES) the wind speed in a plurality of measurement planes. The second step uses the measurements and a Kalman filter (KAL1) to determine the induction factors between measurement planes denoted a_{PM} . The third step uses the induction factors between measurement planes a_{PM} to determine, by means of a Kalman filter (KAL2), the wind induction factor between a measurement plane and the rotor plane denoted a_{PR} .

1) Measuring wind speed

During this step, the wind speed is continuously measured in at least three measurement planes remote from the wind turbine using the LIDAR sensor. Thus, the wind speed can be known upstream of the wind turbine in three measurement planes located at different distances from the wind turbine. In other words, the wind speed can be known at three distances from the rotor plane of the wind turbine. For this step, the three wind components (longitudinal, lateral and vertical) are considered, as well as the variations of the wind speed in the measurement plane (for example, the wind speed increases with the altitude).

According to one embodiment of the invention, the wind speed is measured in at least four measurement planes, so as to increase the precision of the knowledge of the wind upstream of the wind turbine and, consequently, the precision of the estimation of the wind induction factor at the rotor plane.

According to one embodiment of the invention, the measurement planes can be separated by a longitudinal distance (along the x axis of figure 1) ranging between 50 and 400 m from the rotor plane. Thus, it is possible to determine the development of the wind speed over a long distance upstream of the wind turbine, which also allows the precision of the estimation of the wind induction factors to be increased.

According to a non-limiting embodiment, the LIDAR sensor can carry out measurements for ten measurement planes, in particular they can be respectively located at distances of 50, 70, 90, 100, 110, 120, 140, 160, 180 and 200 m from the rotor plane.

2) Determining induction factors between measurement planes

During this step, at least two wind induction factors between two measurement planes are determined in real time. In other words, at least a first wind induction factor is determined

between a first measurement plane and a second measurement plane, and a second wind induction factor is determined between a third measurement plane and a fourth measurement plane (at most one of the third and fourth measurement planes corresponds to one of the first and second measurement planes). In a simplified manner, these induction factors are called induction factors between measurement planes throughout the remainder of the description.

10 According to the invention, the induction factors between measurement planes are determined by means of measurements of the wind speed and by means of a Kalman filter, in particular a linear Kalman filter.

15 Advantageously, for this step and for the embodiment for which the measurement is carried out for at least four measurement planes, at least three wind induction factors can be determined between measurement planes. Thus, it is possible to increase the precision of the wind braking phenomenon upstream of the wind turbine and, consequently, the precision of the estimation of the wind induction factor at the rotor plane.

25 According to one embodiment of the invention, an induction factor can be determined between measurement planes for the measurement plane closest to the rotor plane, so as to have information relative to the closest possible wind field of the rotor plane.

30 According to one implementation of the invention, the wind induction factors between measurement planes can be determined, for measurement planes with the same spacing. For example, the spacing can be 50 m and a first induction factor can be determined for measurement planes located at 70 and 120 m, and a second induction factor can be determined for measurement planes located at 90 and 140 m.

Preferably, the spacing between the measurement planes used for the wind induction factors between measurement planes can be

identical to the distance between the rotor plane and the closest measurement plane. Thus, the model of the induction factor is simplified, which particularly facilitates the resolution of the Kalman filter.

5

For example, by combining the variants described above, if the first measurement plane is 50 m from the rotor plane, a first induction factor can be determined for measurement planes located at 50 and 100 m, a second induction factor can be determined for measurement planes located at 70 and 120 m and a third induction factor can be determined for measurement planes located at 90 and 140 m.

According to one embodiment of the invention, the Kalman filter can be implemented by means of the various steps described hereafter. The steps are described for an embodiment in which a first induction factor $a_{50,100}$ is determined for measurement planes located at 50 and 100 m, a second induction factor $a_{70,120}$ is determined for measurement planes located at 70 and 120 m and a third induction factor $a_{90,140}$ is determined for measurement planes located at 90 and 140 m.

The following only shows how to estimate $a_{50,100}$ in real time; $a_{70,120}$ and $a_{90,140}$ are obtained in exactly the same way. Since u_{50} , u_{100} are available in real time, it is possible for the induction factor definition equation to be used directly to determine $a_{50,100}$. However, this method has two disadvantages. On the one hand, the information on the standard deviation of the estimated wind speeds u_{50} , u_{100} is not used. Therefore, the standard deviation of the estimate $a_{50,100}$ cannot be known. On the other hand, there could be a problem in terms of computational stability for low speeds, i.e. when u_{100} is close to zero.

$a_{50,100}(k)$ denotes the induction factor at the time k . It is clear that the variation $a_{50,100}(k) - a_{50,100}(k - 1)$ is relatively small. Consequently, the following can be written as:

$$a_{50,100}(k) = a_{50,100}(k - 1) + \eta(k - 1),$$

where $\eta(k-1)$ is used to describe the variation of $a_{50,100}(k)$ over time.

5 The first induction factor definition equation is re-written as:

$$u_{100}(k)a_{50,100}(k) = u_{50}(k)$$

10 Since the estimates $u_{50}(k)$, $u_{100}(k)$ contain noise, a more realistic model of the above equation is:

$$(u_{100}(k) + \epsilon_{100}(k))a_{50,100}(k) = u_{50}(k) + \epsilon_{50}(k)$$

15 where $\epsilon_{50}(k)$, $\epsilon_{100}(k)$ are the noises for $u_{50}(k)$, $u_{100}(k)$, respectively. The preceding equation then can be re-written as:

$$u_{100}(k)a_{50,100}(k) = u_{50}(k) + \epsilon_{50}(k) - \epsilon_{100}(k)a_{50,100}(k)$$

20 Combining the preceding equations provides the following state equation:

$$\begin{cases} a_{50,100}(k) = a_{50,100}(k-1) + \eta(k-1), \\ u_{50}(k) = u_{100}(k)a_{50,100}(k) + \mu(k) \end{cases}$$

$$\mu(k) = \epsilon_{100}(k)a_{50,100}(k) - \epsilon_{50}(k)$$

25 One way of estimating the unknown state vector $a_{50,100}(k)$, which can take into account information relating to $\epsilon(k)$ and $\mu(k)$, involves applying a Kalman filtering algorithm, called Kalman filter. In practice, this filter provides the solution to the following problem:

$$\min_{a_{50,100}(k)} J(k)$$

30

With

$$J(k) = (a_{50,100}(0) - \bar{a}_{50,100}(0))^T P_0^{-1} (a_{50,100}(0) - \bar{a}_{50,100}(0)) + \sum_{j=1}^k (\eta(j-1)^T Q^{-1} \eta(j-1) + \mu(j)^T R^{-1} \mu(j))$$

- 5 where P_0 , Q , R are weighting matrices of a suitable size, $a_{50,100}(0)$ covered with a bar line is the mean value of the initial state $a_{50,100}(0)$.

10 In order to overcome the optimization problem, using the Kalman filtering algorithm, the following assumptions are formulated. These hypotheses mainly relate to a mathematical interpretation for P_0 , Q and R .

- 15 • $a_{50,100}(0)$ is a random vector not correlated to the noises $\varepsilon(k)$ and $u(k)$.

- $a_{50,100}(0)$ has a known mean with P_0 as the covariance matrix, [Math 9]

i.e.

$$P_0 = E[(a_{50,100}(0) - \bar{a}_{50,100}(0))(a_{50,100}(0) - \bar{a}_{50,100}(0))^T]$$

with $\bar{a}_{50,100}(0)$ being the mean value of the initial state.

20

- $\varepsilon(k)$ and $\mu(k)$ are mean-zero and uncorrelated white noises with covariance matrices Q and R , respectively, i.e.

$$\begin{aligned} E[\eta(k)\eta(j)^T] &= \begin{cases} Q, & \text{if } k=j, \\ 0, & \text{if } k \neq j \end{cases} \\ E[\mu(k)\mu(j)^T] &= \begin{cases} R, & \text{if } k=j, \\ 0, & \text{if } k \neq j \end{cases} \\ E[\eta(k)\mu(j)^T] &= 0, \text{ for all } k, j \end{aligned}$$

25

It is to be noted that this hypothesis also implies that Q and R are semi-defined positive symmetrical matrices.

The following notations are adopted:

30

- $\hat{a}_{50,100}(k|k-1)$ is the estimate of $a_{50,100}(k)$ provided by the

time measurements $k - 1$;

- $\hat{a}_{50,100}(k|k)$ is the estimate of $a_{50,100}(k)$ provided by the time measurements k ;

5

- $P(k|k - 1)$ is the covariance matrix of $a_{50,100}(k)$ provided by the time measurements $k - 1$;

- $P(k|k)$ is the covariance matrix of $a_{50,100}(k)$ provided by the
10 time measurements k .

Subsequently, the Kalman filtering algorithm can be summarized as follows:

15 • Time update equation:

[Math 11]

$$\begin{cases} \hat{a}_{50,100}(k|k-1) &= \hat{a}_{50,100}(k-1|k-1) \\ P(k|k-1) &= P(k-1|k-1) + Q \end{cases};$$

- Measurement update equation:

20

$$\begin{cases} K(k) &= P(k|k-1)u_{100}(k)^T \left(P(k|k-1) + u_{100}(k)Ru_{100}(k)^T \right)^{-1} \\ \hat{a}_{50,100}(k|k) &= \hat{a}_{50,100}(k|k-1) + K(k) (u_{50}(k) - u_{100}(k)\hat{x}(k|k-1)), \\ P(k|k) &= (I - K(k)) P(k|k-1) \end{cases}$$

By applying these steps, it is possible to determine the induction factor $a_{50,100}$. These steps are repeated to determine
25 the induction factors $a_{70,120}$ and $a_{90,140}$.

Figure 6 illustrates, in a non-limiting manner, induction factors between measurement planes $a_{50,100}$ (dark grey), $a_{70,120}$ (dashed-medium grey) and $a_{90,140}$ (dashed-light grey) as a function
30 of time T in seconds. These induction factors are obtained by the method according to the invention. On the one hand, the phenomenon of wind braking can be seen: the closer to the wind turbine, the lower the induction factor between measurement

planes. On the other hand, it can be seen that the induction factor is variable over time.

Figure 7 illustrates, in a non-limiting manner, the development of the induction factor between measurement planes a as a function of the distance D in metres from the first measurement plane for a given time. The wind braking phenomenon also can be seen, as well as the non-linearity of the induction factor as a function of the distance.

3) Determining the induction factor between a measurement plane and the rotor plane

During this step, the wind induction factor between one of the measurement planes and the rotor plane is determined in real time. Thus, it is possible to show the development of the wind at the rotor, taking into account the physical phenomena, in particular the braking of the wind. According to the invention, the wind induction factor is determined between a measurement plane and the rotor plane by means of the induction factors determined in the preceding step and by means of a Kalman filter, in particular a linear Kalman filter. In a simplified manner, this induction factor is called the induction factor in the rotor plane throughout the remainder of the description.

Preferably, the wind induction factor can be determined between the measurement plane closest to the rotor and the rotor plane.

For example, during this step, the induction factor can be determined between a measurement plane located 50 m from the rotor and the rotor plane.

According to one embodiment of the invention, the Kalman filter can be implemented by means of the various steps described hereafter. The steps are described for an embodiment for which $a_{50,100}$, $a_{70,120}$ and $a_{90,140}$ were determined and for which $a_{0,50}$ is determined, i.e. the induction factor between a measurement plane located at 50 m and the rotor plane.

Using $a_{50,100}$, $a_{70,120}$ and $a_{90,140}$, the main idea of estimating $a_{0,50}$ is to assume that $a_{0,50}$, $a_{50,100}$, $a_{70,120}$ and $a_{90,140}$ are a function of the distance. To this end, the following relation is assumed:

5

$$\begin{cases} a_{0,50} &= 0x_1 + x_2, \\ a_{50,100} &= 50x_1 + x_2, \\ a_{70,120} &= 70x_1 + x_2, \\ a_{90,140} &= 90x_1 + x_2, \end{cases},$$

where x_1 , x_2 are unknown parameters, which must be determined.

As $a_{50,100}$, $a_{70,120}$ and $a_{90,140}$ slowly change over time, the same is
10 the case for x_1 and x_2 . Consequently, the following can be expressed:

$$\begin{cases} x_1(k) &= x_1(k-1) + \zeta_1(k-1), \\ x_2(k) &= x_2(k-1) + \zeta_2(k-1) \end{cases},$$

15 where $\zeta_1(k)$, $\zeta_2(k)$ are used to characterize the variation of $x_1(k)$, $x_2(k)$. The following is noted:

$$x(k) = \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix}, \quad \zeta(k) = \begin{bmatrix} \zeta_1(k) \\ \zeta_2(k) \end{bmatrix}.$$

20 The following then can be written in compact form:

$$x(k) = x(k-1) + \zeta(k-1).$$

A more realistic model that takes into account noises is as
25 follows:

$$\begin{cases} a_{50,100}(k) &= [50 \ 1] x(k) + \epsilon_1(k), \\ a_{70,120}(k) &= [70 \ 1] x(k) + \epsilon_2(k), \\ a_{90,140}(k) &= [90 \ 1] x(k) + \epsilon_3(k), \end{cases}$$

where ϵ_1 , ϵ_2 , ϵ_3 are the noises of the estimates $a_{50,100}(k)$,

$a_{70,120}(k)$ and $a_{90,140}(k)$. It is then possible to note:

$$y(k) = \begin{bmatrix} a_{50,100}(k) \\ a_{70,120}(k) \\ a_{90,140}(k) \end{bmatrix}, C = \begin{bmatrix} 50 & 1 \\ 70 & 1 \\ 90 & 1 \end{bmatrix}, \epsilon(k) = \begin{bmatrix} \epsilon_1(k) \\ \epsilon_2(k) \\ \epsilon_3(k) \end{bmatrix}.$$

5 The following then can be written in compact form:

$$y(k) = Cx(k) + \epsilon(k).$$

Combining the preceding equations provides the following state
10 equation:

$$\begin{cases} x(k) = x(k-1) + \zeta(k-1) \\ y(k) = Cx(k) + \epsilon(k) \end{cases}.$$

As for $a_{50,100}(k)$, $a_{70,120}(k)$, $a_{90,140}(k)$, one way of obtaining
15 $x(k)$, which takes into account the noises $\zeta(k)$, $\epsilon(k)$, uses the linear Kalman filter technique. To this end, the same steps as those described for the preceding step are applied.

Once $x(k)$ is estimated, the induction factor $a_{0,50}$ can be computed
20 as follows:

$$a_{0,50}(k) = [0 \ 1]x(k).$$

Figure 8 illustrates, in a non-limiting manner, the induction
25 factor at the rotor plane $a_{0,50}$ as a function of time T in seconds. This induction factor is obtained by the method according to the invention on the basis of the induction factors of figure 6. On the one hand, the wind braking phenomenon (induction) can be seen: the induction factor at the rotor (figure 8) is less than
30 the induction factors between measurement planes (figure 6). On the other hand, it can be seen that the induction factor is variable over time. Furthermore, the developments from one induction factor to another induction factor are different.

Figure 9 is a curve similar to figure 7, which shows, in a non-limiting manner, the development of the induction factor a as a function of the distance D in metres from the first measurement plane for a given time. The wind braking phenomenon also can be seen, as well as the non-linearity of the induction factor as a function of the distance.

Thus, the method according to the invention allows the wind induction factor to be determined between a measurement plane and the rotor plane, in real time.

Applications

Moreover, the invention relates to a method for determining the wind speed in the rotor plane of a wind turbine equipped with a LIDAR sensor. The following steps are implemented for this method:

- a wind induction factor is determined between a measurement plane and the rotor plane of the wind turbine by means of the method according to any one of the combinations of variants described above;

- the wind speed is determined in the rotor plane of the wind turbine as a function of the wind induction factor determined in the preceding step, and by means of at least one wind speed measurement used in the preceding step, the wind speed measurement corresponds to the wind speed in the measurement plane relative to the measurement plane used for the induction factor.

In other words, if, in the first step, the induction factor is determined between a measurement plane located at the distance d_2 from the rotor plane, during the step of determining the wind speed in the rotor plane, the measurement of the wind speed in the measurement plane located at the distance d_2 from the rotor plane is used.

The method according to the invention allows the wind speed in the rotor plane to be determined online, in a simple and precise manner (since it takes into account the physical phenomena in the induction zone).

5

According to one embodiment, the wind speed in the rotor plane can be determined by multiplying (product) the wind induction factor and the relative wind speed. The equation of the definition of the induction factor then can be used. Indeed,
10 this equation can be written as:

$$u_0 = u_{d2} \times a_{0,d2} .$$

With the speed u_{d2} being measured and the induction factor $a_{0,d2}$
15 being determined by the method for determining the induction factor.

Figure 3 illustrates, schematically and in a non-limiting manner, the steps of the method for determining the wind speed in the rotor plane. The first steps are identical to the steps of figure
20 2. The first step is a step of measuring (MES) the wind speed in a plurality of measurement planes. The second step uses the measurements and a Kalman filter (KAL1) to determine the induction factors between measurement planes denoted a_{PM} . The
25 third step uses the induction factors between measurement planes a_{PM} to determine, by means of a Kalman filter (KAL2), the wind induction factor between a measurement plane and the rotor plane denoted a_{PR} . The fourth step (VIV) determines the wind speed in the rotor plane u_0 on the basis of the induction factor between
30 a measurement plane and the rotor plane a_{PR} and a measurement of the wind speed in the considered measurement plane.

The present invention also relates to a method for controlling a wind turbine equipped with a LIDAR sensor. The following steps
35 are implemented for this method:

- the wind speed is determined in the rotor plane by means of the method for determining the wind speed according to any one

of the variants described above;

- the wind turbine is controlled as a function of the wind speed at the rotor plane.

5

The precise and real-time knowledge of the wind speed in the rotor plane allows the wind turbine to be suitably controlled, in terms of minimizing the effects on the structure of the wind turbine and of maximizing the recovered power. Indeed, by means
10 of this control, the LIDAR allows the loads on the structure to be reduced, the blades and the mast of which structure represent 54% of the cost. Consequently, the use of a LIDAR sensor allows the wind turbine structure to be optimized, and therefore allows the costs and maintenance to be reduced.

15

According to one implementation of the invention, the angle of incline of the blades and/or the electrical recovery torque of the wind turbine generator can be controlled as a function of the wind speed. Other types of regulation device can be used.

20

According to one embodiment of the invention, the angle of incline of the blades and/or the electrical recovery torque are determined by means of maps of the wind turbine as a function of the wind speed at the rotor. For example, the control method
25 described in patent application FR 2976630 A1 (US 2012/0321463) can be applied.

Figure 4 illustrates, schematically and in a non-limiting manner, the steps of the method for determining the control of a wind turbine. The first steps are identical to the steps of figure
30 3. The first step is a step of measuring (MES) the wind speed in a plurality of measurement planes. The second step uses the measurements and a Kalman filter (KAL1) to determine the induction factors between measurement planes denoted a_{PM} . The
35 third step uses the induction factors between measurement planes a_{PM} to determine, by means of a Kalman filter (KAL2), the wind induction factor between a measurement plane and the rotor plane denoted a_{PR} . The fourth step (VIV) determines the wind speed in

the rotor plane u_0 on the basis of the induction factor between a measurement plane and the rotor plane a_{PR} and a wind speed measurement in the considered measurement plane. The fifth step (CON) relates to controlling the wind turbine as a function of the wind speed u_0 in the rotor plane.

Furthermore, the invention relates to a method for diagnosing and/or monitoring a wind turbine equipped with a LIDAR sensor, in which the following steps are implemented:

- a wind induction factor is determined between a measurement plane and the rotor plane of the wind turbine by means of the method for determining the induction factor according to any one of the combinations of variants described above;

- the aerodynamic power collected from the wind by the wind turbine is determined by means of the induction factor determined in the preceding step; and

- the operation of the wind turbine is diagnosed and/or monitored as a function of the aerodynamic power determined in the preceding step.

With the induction factor expressing the braking of the wind due to the presence of the wind turbine in the wind field, it is possible to determine, on the basis of this induction factor, the aerodynamic power collected from the wind by the wind turbine. According to one embodiment, this collected aerodynamic power P_{aero} can be determined by means of the induction factor a , the speed of the free wind V_{inf} , the air density ρ , the surface of the wind turbine A_d ,

$$P_{aero} = 2\rho A_d V_{inf}^3 a(1-a)^2.$$

The collected aerodynamic power provides information relating to the operation of the wind turbine, which allows a diagnosis and/or monitoring of the operation of the wind turbine to be carried out. The main idea is to compare the electric power

produced by the wind turbine with the theoretical electric power provided by the preceding equation.

5 By using the ratio between the two powers, a diagnosis and/or monitoring of the operation and of the effective aerodynamic output of the wind turbine can be carried out.

10 Having a real-time update of the induction factor also allows the aerodynamic thrust loads applied to the wind turbine to be quantified, and allows an estimate of the cumulative fatigue damage to be deduced therefrom. According to one implementation of the invention, this can be achieved by virtue of the relationship linking the thrust coefficient C_T to the induction factor (Burton, Wind Energy handbook, ch.3.2), which can be
15 written as $C_T = 4a(1-a)$.

In addition, an online estimate of the induction factor can be used to develop and update simplified wind turbine wake models in real time. This allows operating diagnostics to be developed
20 to the scale of a wind farm, and allows at risk zones to be identified where wind turbines are found in the wake of other wind turbines.

Figure 5 illustrates, schematically and in a non-limiting manner,
25 the steps of the method for determining the wind speed in the rotor plane. The first steps are identical to the steps of figure 2. The first step is a step of measuring (MES) the wind speed in a plurality of measurement planes. The second step uses the measurements and a Kalman filter (KAL1) to determine the
30 induction factors between measurement planes denoted a_{PM} . The third step uses the induction factors between measurement planes a_{PM} to determine, by means of a Kalman filter (KAL2), the wind induction factor between a measurement plane and the rotor plane denoted a_{PR} . The fourth step (PUI) determines the aerodynamic
35 power P_{aero} collected from the wind on the basis of the induction factor between a measurement plane and the rotor plane a_{PR} and a wind speed measurement in the measurement plane. The fifth step (DIA) carries out the diagnosis or the monitoring of the wind

turbine as a function of the collected aerodynamic power P_{aero} .

Moreover, the invention relates to a computer program product,
which comprises code instructions designed to implement the
5 steps of one of the previously described methods (method for
determining an induction factor, method for determining the
speed in the rotor plane, control method, diagnostic and/or
monitoring method). The program is executed on a processing unit
of the LIDAR sensor, or on any similar means, linked to the
10 LIDAR sensor or to the wind turbine.

According to one aspect, the present invention also relates to
a LIDAR sensor for a wind turbine, which comprises a processing
unit configured to implement one of the previously described
15 methods (method for determining an induction factor, method for
determining the speed in the rotor plane, control method,
diagnostic and/or monitoring method).

According to one implementation of the invention, the LIDAR
20 sensor can be a scanned LIDAR, continuous LIDAR or pulsed LIDAR
sensor. Preferably, the LIDAR sensor is a pulsed LIDAR sensor.

The invention also relates to a wind turbine, in particular an
offshore (at sea) or onshore (on land) wind turbine equipped
25 with a LIDAR sensor as described above. According to one
embodiment of the invention, the LIDAR sensor can be disposed
on the nacelle of the wind turbine. The LIDAR sensor is
controlled so as to measure the wind upstream of the wind turbine
(i.e. before the wind turbine and along its longitudinal axis,
30 designated by the x axis in figure 1). According to one
embodiment, the wind turbine can be a wind turbine according to
the wind turbine illustrated in figure 1.

For the embodiment of the control method, the wind turbine can
35 comprise control means, for example, controlling the pitch angle
of a blade of the wind turbine or the electrical torque, in
order to implement the method according to the invention.

For the embodiment of the diagnostic and/or monitoring method, the wind turbine can comprise means for diagnosing and/or monitoring the operation of the wind turbine.

Patentkrav

1. Fremgangsmåde til bestemmelse af en vindinduktionsfaktor mellem et måleplan (PM) og rotorplanet (PR) i en vindmølle (1),
5 hvilken vindmølle (1) er udstyret med en LIDAR-sensor (2), der udfører en måling vedrørende vindhastigheden i mindst tre måleplaner (PM) fjernt fra vindmøllen (1), hvilken vindinduktionsfaktoren udgør en vindbremsningskoefficient mellem to punkter i afstand fra hinanden opstrøms for vindmøllen
10 (1), idet bremsningen skyldes driften af vindmøllen (1) i vindfeltet, kendetegnet ved, at følgende trin udføres:
a) vindhastigheden måles i mindst tre måleplaner (PM) fjernt fra vindmøllen ved hjælp af LIDAR-sensoren (2)
b) mindst to vindinduktionsfaktorer mellem to af måleplanerne
15 (PM) bestemmes ved hjælp af målingerne af vindhastigheden ved måleplanerne og et lineært Kalman-filter, og
c) vindinduktionsfaktoren bestemmes mellem et måleplan (PM) og rotorplanet (PR) i vindmøllen (1) ved hjælp af induktionsfaktorerne mellem to bestemte måleplaner (PM) og ved
20 hjælp af et lineært Kalman-filter.
2. Fremgangsmåde ifølge krav 1, hvorved mindst to vindinduktionsfaktorer bestemmes mellem måleplanerne (PM) med kendte mellemrum, fortrinsvis med samme afstand, og hvorved
25 afstanden fortrinsvis er lig med afstanden mellem rotorplanet (PR) og det måleplan (PM), der er tættest på rotorplanet (PR).
3. Fremgangsmåde ifølge et af de foregående krav, hvorved målingen af vindhastigheden udføres i mindst fire måleplaner
30 (PM), og mindst tre vindinduktionsfaktorer bestemmes mellem to måleplaner (PM).
4. Fremgangsmåde til bestemmelse af vindhastigheden i rotorplanet i en vindmølle (1), der er udstyret med en LIDAR-sensor (2), kendetegnet ved, at følgende trin udføres:
35 a) en vindinduktionsfaktor bestemmes mellem et måleplan (PM) og rotorplanet (PR) i en vindmølle ved hjælp af fremgangsmåden ifølge et af kravene 1 til 3, og

b) vindhastigheden bestemmes i rotorplanet (PR) som en funktion af vindinduktionsfaktoren mellem et måleplan (PM) og rotorplanet (PR) i en vindmølle (1) og ved hjælp af måling af vindhastigheden i det til vindinduktionsfaktoren relaterede måleplan (PM).

5

5. Fremgangsmåde ifølge krav 4, hvorved vindhastigheden i rotorplanet (PR) svarer til multiplikationen af vindinduktionsfaktoren mellem et måleplan (PM) og rotorplanet (PR) i en vindmølle (1) med vindhastigheden i det til vindinduktionsfaktoren relaterede måleplan (PM).

10

6. Fremgangsmåde til styring af en vindmølle (1), der er udstyret med en LIDAR-sensor (2), kendetegnet ved, at følgende trin udføres:

15

- a) vindhastigheden bestemmes i rotorplanet (PR) i vindmøllen (1) ved hjælp af fremgangsmåden ifølge et af kravene 4 eller 5
- b) vindmøllen (1) styres som funktion af vindhastigheden ved rotorplanet (PR).

20

7. Fremgangsmåde til diagnosticering og/eller overvågning af en vindmølle, der er udstyret med en LIDAR-sensor, kendetegnet ved, at følgende trin udføres:

- a) en vindinduktionsfaktor bestemmes mellem et måleplan (PM) og rotorplanet (PR) i en vindmølle (1) ved hjælp af fremgangsmåden ifølge et af kravene 1 til 3

25

b) den aerodynamiske effekt, som vindmøllen (1) optager fra vinden, bestemmes ved hjælp af den mellem et måleplan (PM) og rotorplanet (PR) i en vindmølle (1) bestemte vindinduktionsfaktor, og

30

c) driften af vindmøllen (1) diagnosticeres og/eller overvåges ved hjælp af den bestemte optagne aerodynamiske effekt.

8. Computerprogramprodukt, kendetegnet ved, at det omfatter kodeinstruktioner, som er beregnet til at udføre trinnene i en fremgangsmåde ifølge et af de foregående krav, når programmet køres på en behandlingsenhed i LIDAR-sensoren (2).

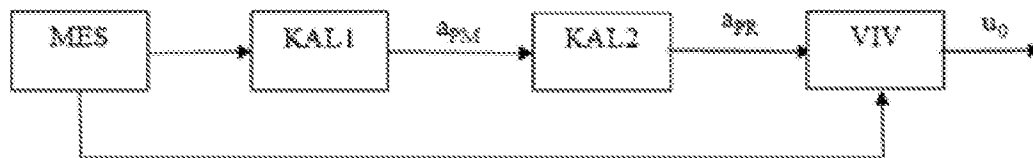
35

9. LIDAR-sensor (2) til en vindmølle, kendetegnet ved, at den

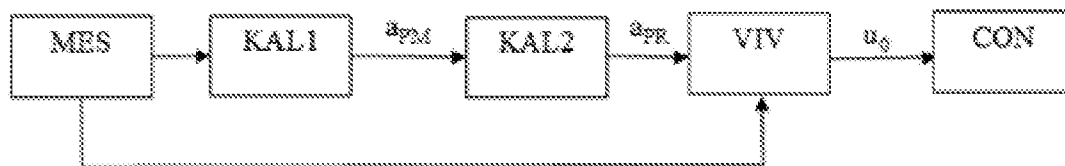
omfatter en behandlingsenhed, der udfører en fremgangsmåde ifølge et af kravene 1 til 7.

10. Vindmølle (1), kendetegnet ved, at den omfatter en LIDAR-sensor (2) ifølge krav 9, hvilken LIDAR-sensor (2) fortrinsvis er placeret på vindmøllens (1) gondol.
- 5

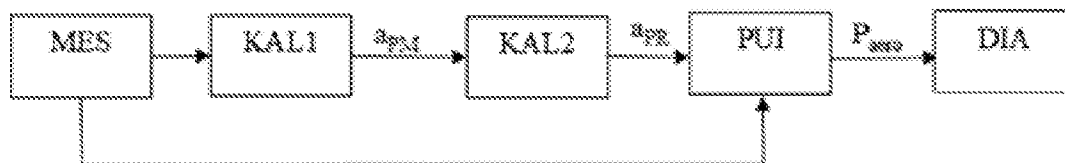
[Fig 3]



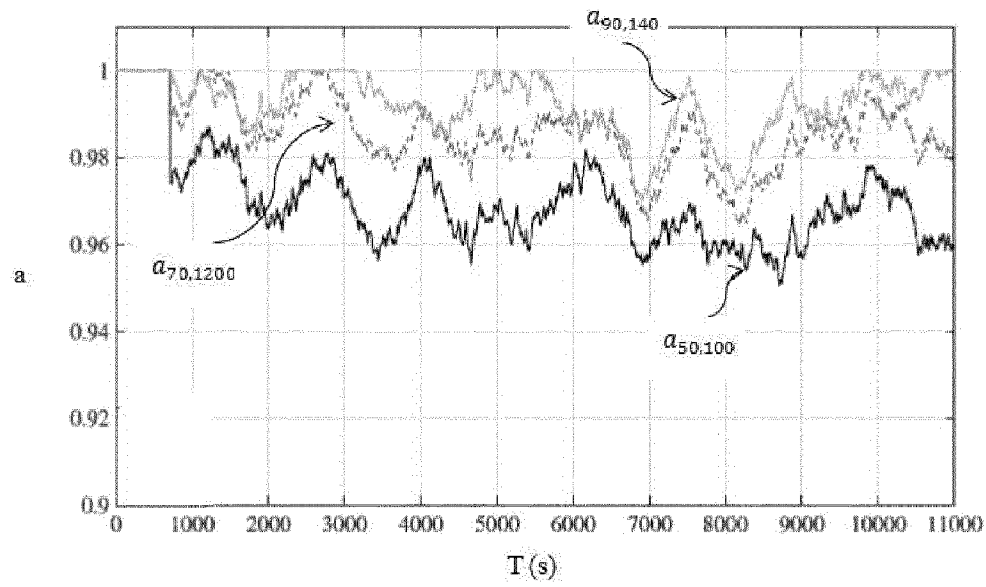
[Fig 4]



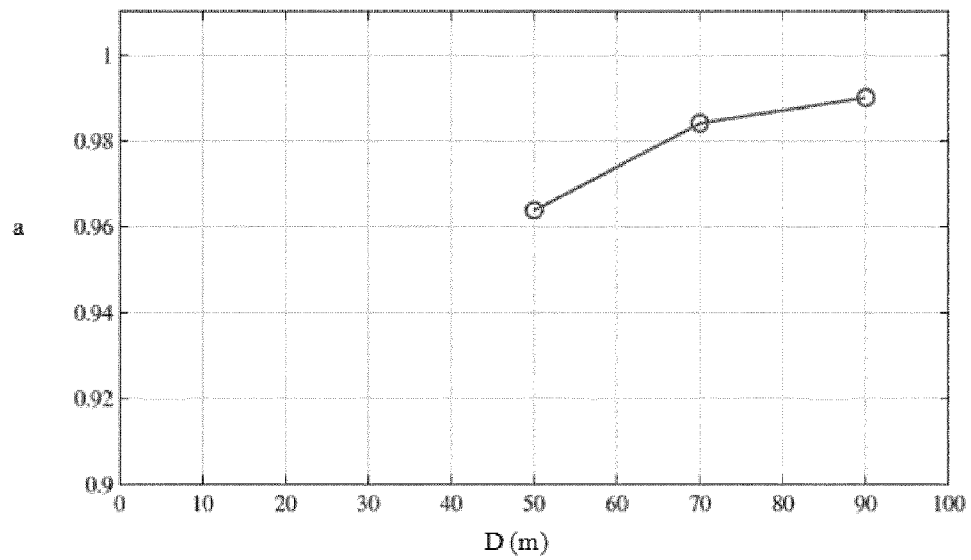
[Fig 5]



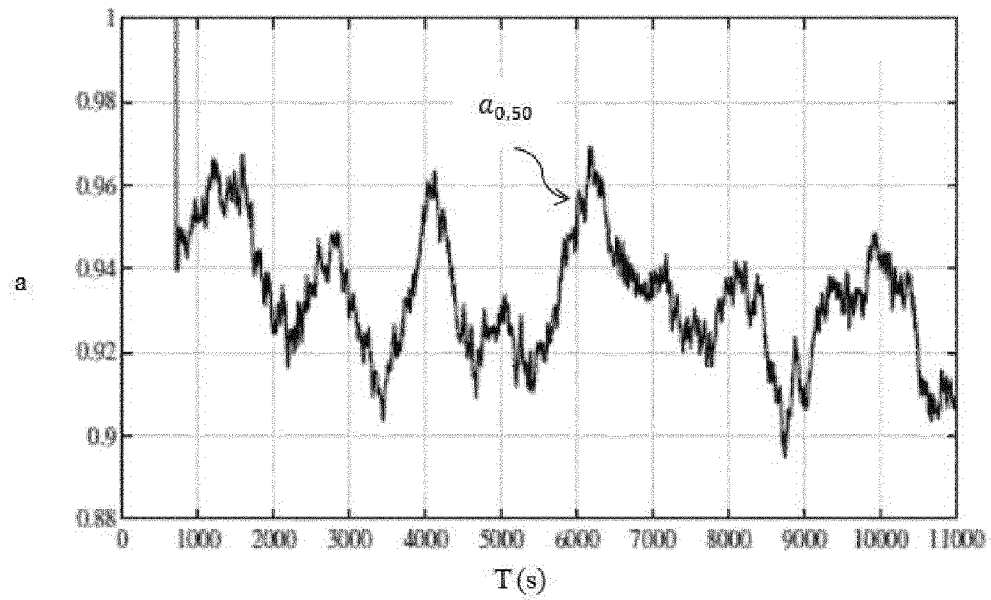
[Fig 6]



[Fig 7]



[Fig 8]



[Fig 9]

